



RIKEN BNL Research Center

Physics Opportunities from the RHIC Isobar Run

This workshop will be held virtually.
January 25–28, 2022

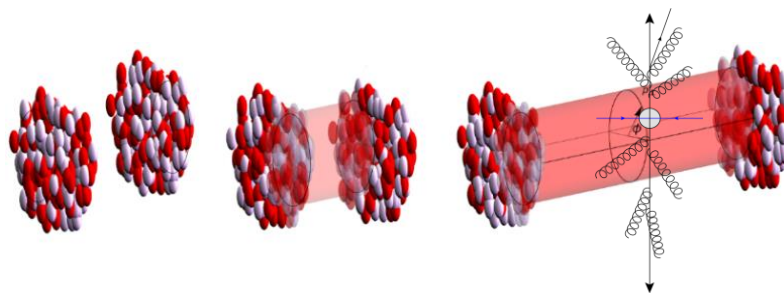
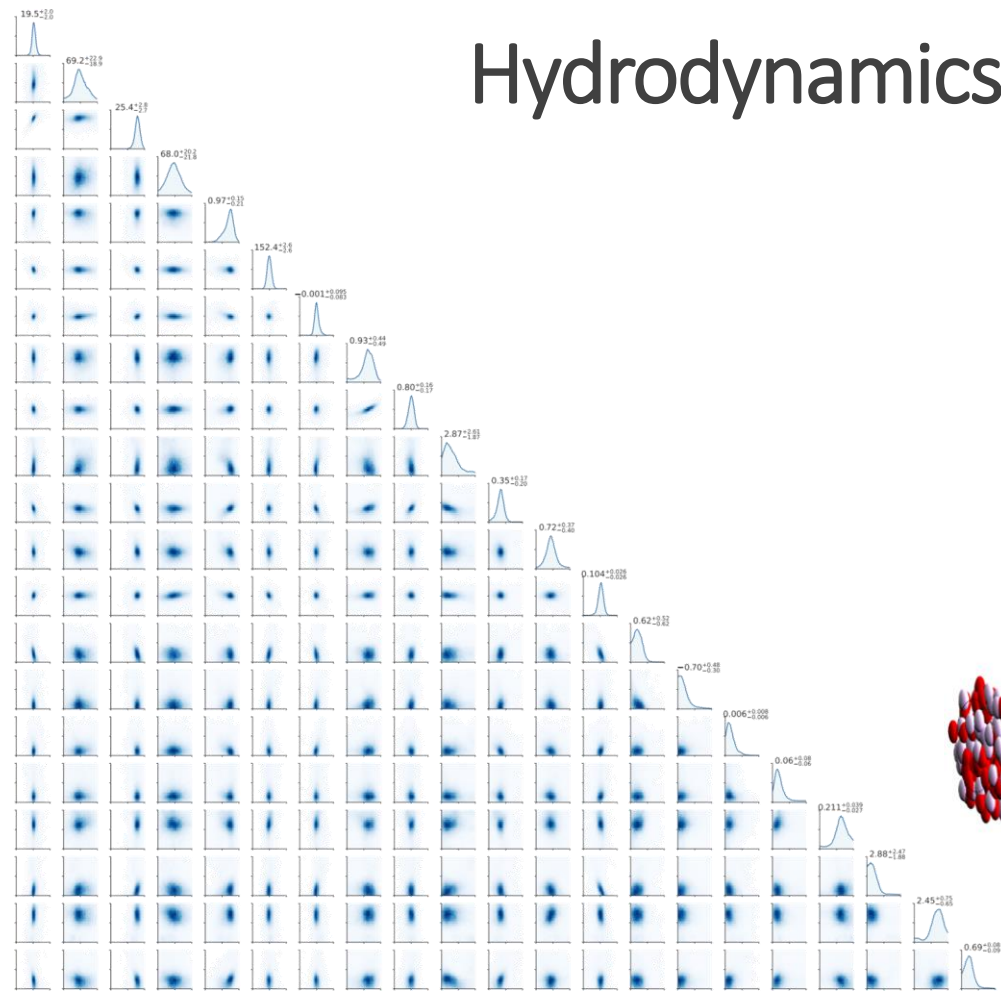


Hydrodynamics and Bayesian Inferences in isobar collisions

Latest *Trajectum* results on Isobar collisions

Based on [2112.13771](#) with Govert Nijs

Big thanks to STAR for sharing their data at very early stage

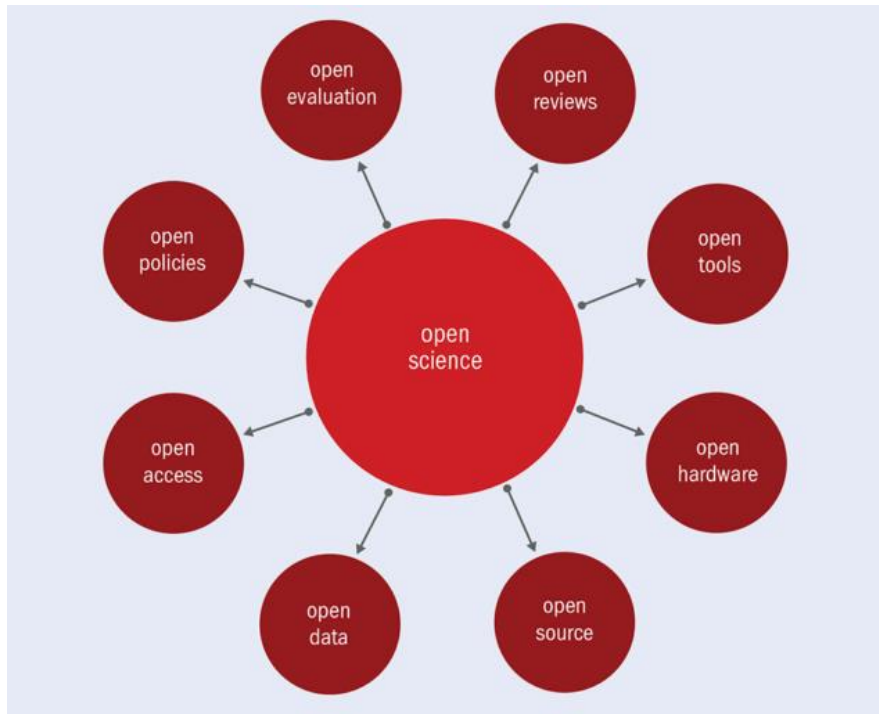


Wilke van der Schee

BNL (virtual non-public workshop)

26 January 2022

A non-public workshop



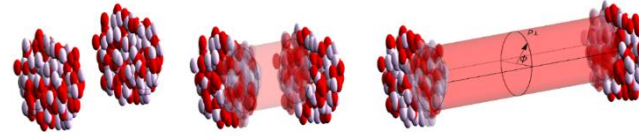
A discussion should be had if a workshop can be closed to the public

- Workshop hardly advertised, complicated to register
- Not ideal for transparent research, towards open science

Different but similar issue for large conferences (e.g. QM)

- A hefty fee may be realistic in terms of cost, but does not align with letting everyone participate (developing countries, students or general public)
- We should not repeat mistakes with journals: journals should be open access, as should zoom links
- Publicly funded science should be publicly available

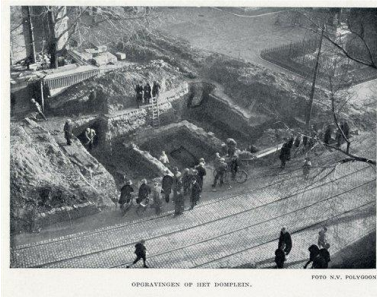
Standard model of heavy ion collisions



(# parameters)

Trajectum

- New public heavy ion code
- Originally Utrecht (now MIT/CERN)
- Fast
- Precise (all cuts equal to experiment)
- Scalable



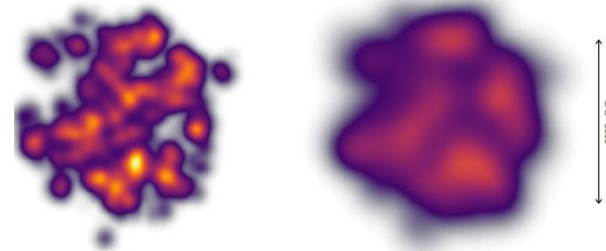
Roman excavations in **Utrecht** in 1929

Initial stage (9)

Subnucleonic structure? (7)

$w = 0.4$ fm

$w = 0.88$ fm

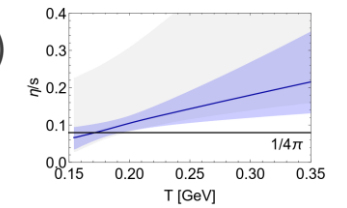


Non-thermal flow? (2)
with *varying speed* (*new*)

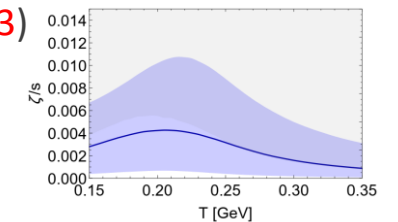
Fluctuations? (1)

Viscous hydrodynamics (9)

Shear viscosity (3)

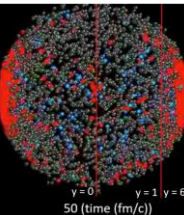


Bulk viscosity (3)



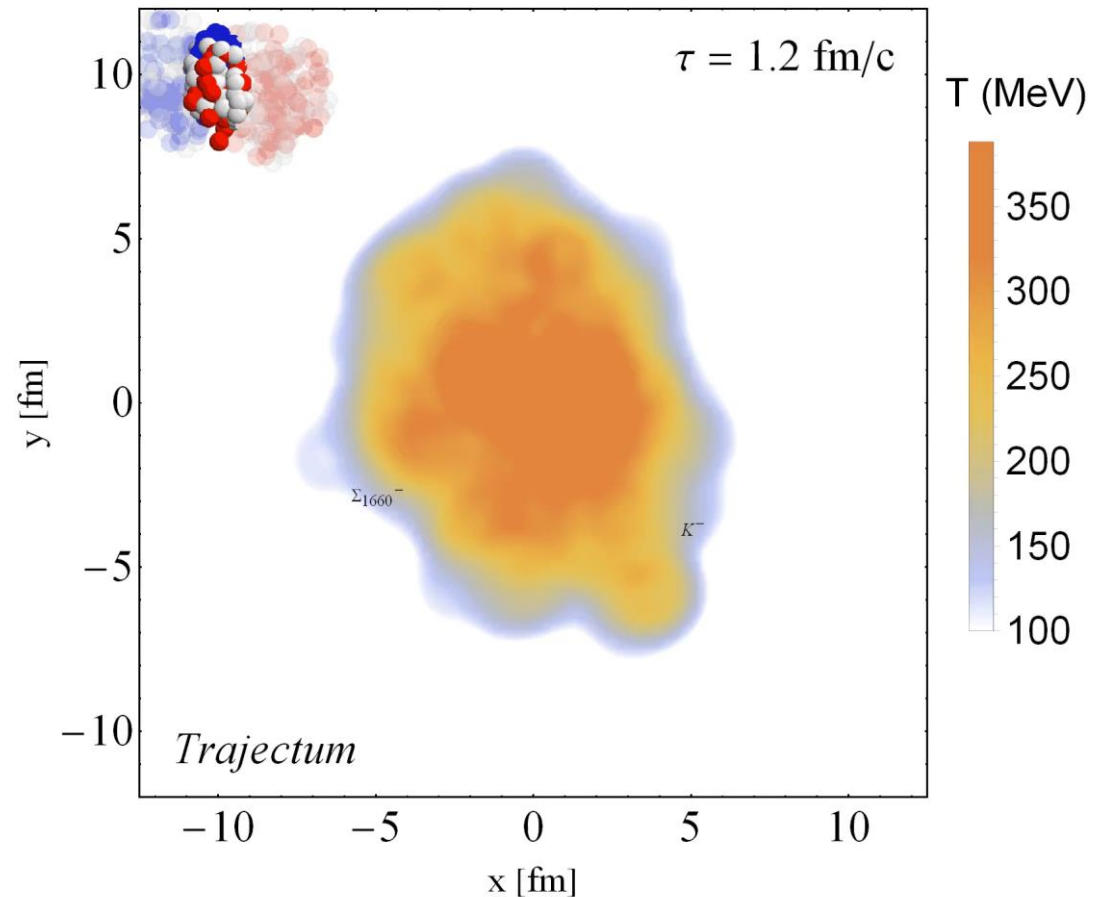
Second order transports: 3 (*new*)

Cascade of hadrons (1)



Trajectum

1. Quite straightforward to use
(see param file, right)
2. Includes analyse routine
 - Parallelised: can analyse unlimited number of events



```

general{
  output=out
  format=smash
  f0500=false
  numevents=1
  seed=7398984.747399307
  debugoutput=true
  numthreads=2
}

entropyacceptanceprobability{
  0:0.0
  24:0.0
  24.5:0.05
  25.5:0.05
  26:0.0
  100:0.0
}

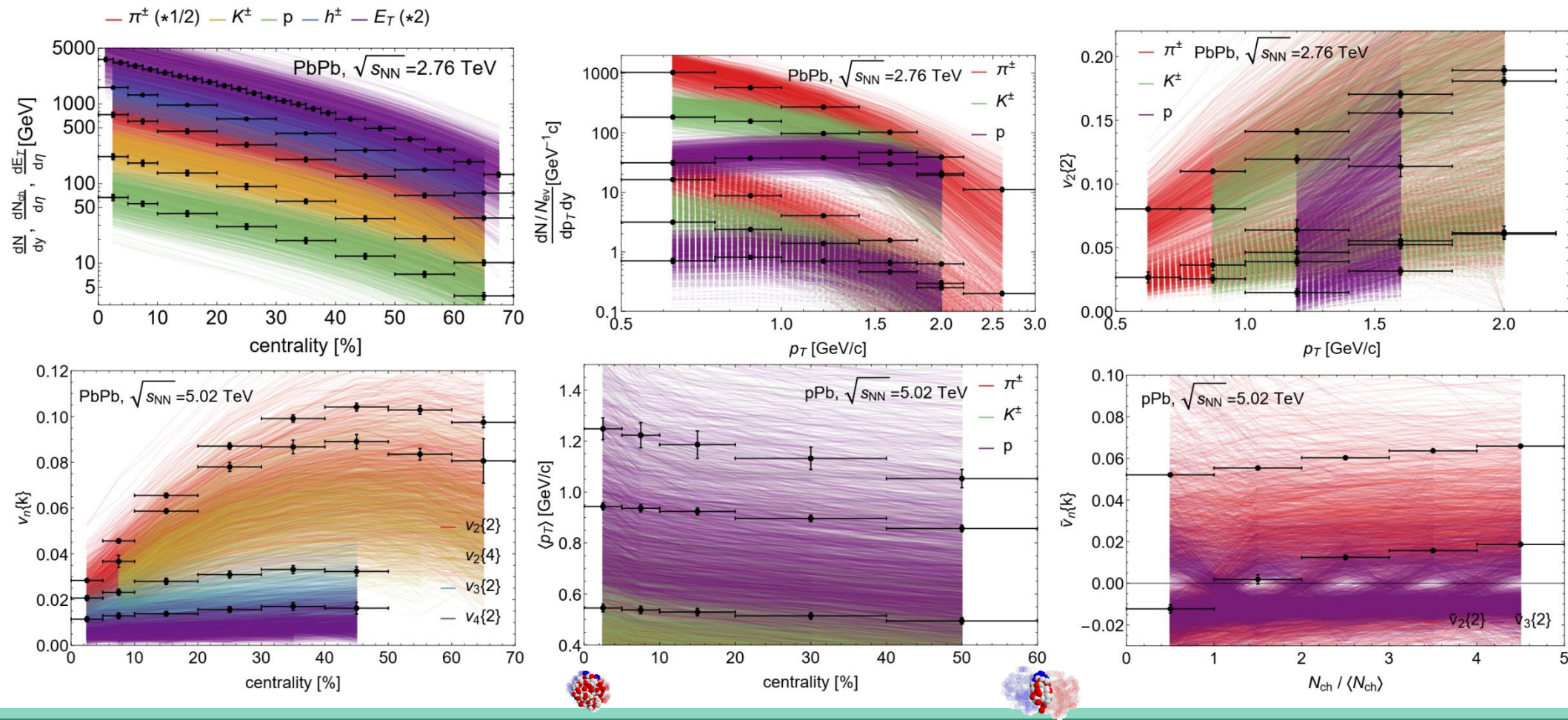
trentosubstructurePbPb{
  dmin=0.63933
  w=0.701919
  sigmann=70.0
  sigmafluct=0.73579
  p=0.14388
  q=1.0
  Eref=0.2
  norm=23.507
  freestreamingreferencetime=1.1708
  freestreamingvelocity=0.62672
  weaktostrong=0.0
  nref=20
  alpha=0
  nc=3.2747
  voverw=0.4892041602706295
}

secondorderhydro{
  numlatticesites=166.0
  latticesize=33.2
}

musclsolverktminmodfastmidpoint{
  cflconstant=0.08
}

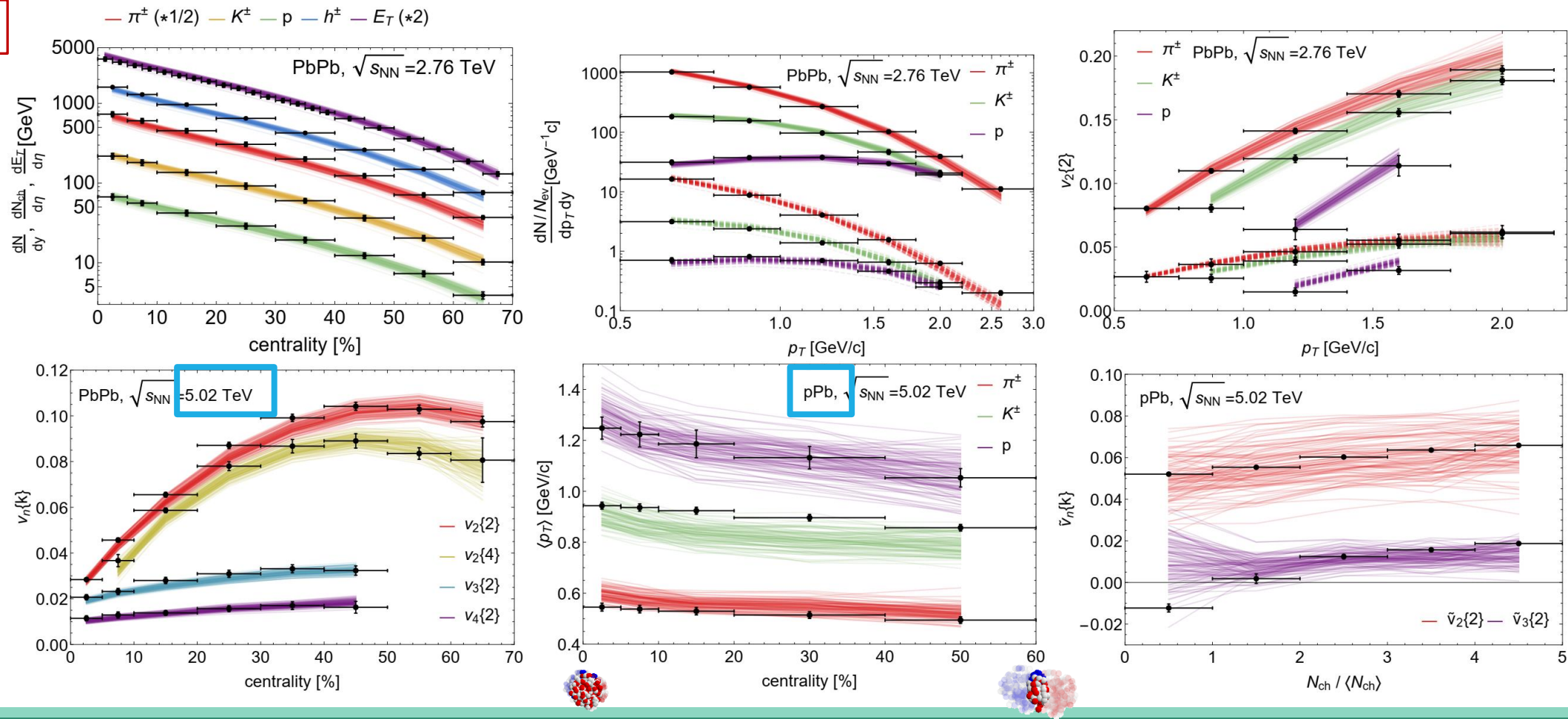
LatticeE0StempdepDuke{
  shearhg=0.0895066
  shearmin=0.0895066
  shearslope=0.43252
  shearcrv=0.231195
  shearrelaxationtime=6.318855
  bulkmax=0.0030138
  bulkT0=0.21471
  bulkwidth=0.10906
  bulkrelaxationtime=0.0687
  deltapiiovertaui=1.3333333333333333
  phi7overpressure=0.128571
  taupiovertaui=1.61033
  lambdapiiovertaui=1.2
  deltaPiiovertaui=0.6666666666666666
  lambdaPiiovertaui=1.6
  phi1overpressure=0
  phi3overpressure=0
  phi6overpressure=0
}

cooperfryehadronizer{
  freezeouttemp=153.456
  rapidityrange=0.1
}
  
```

Experimental observables:
a wealth of data

1. Yields, spectra, identified $v_n\{2\}$ versus p_T , pPb and PbPb (514 datapoints)
2. First study with a comprehensive analysis including p_T -differential observables



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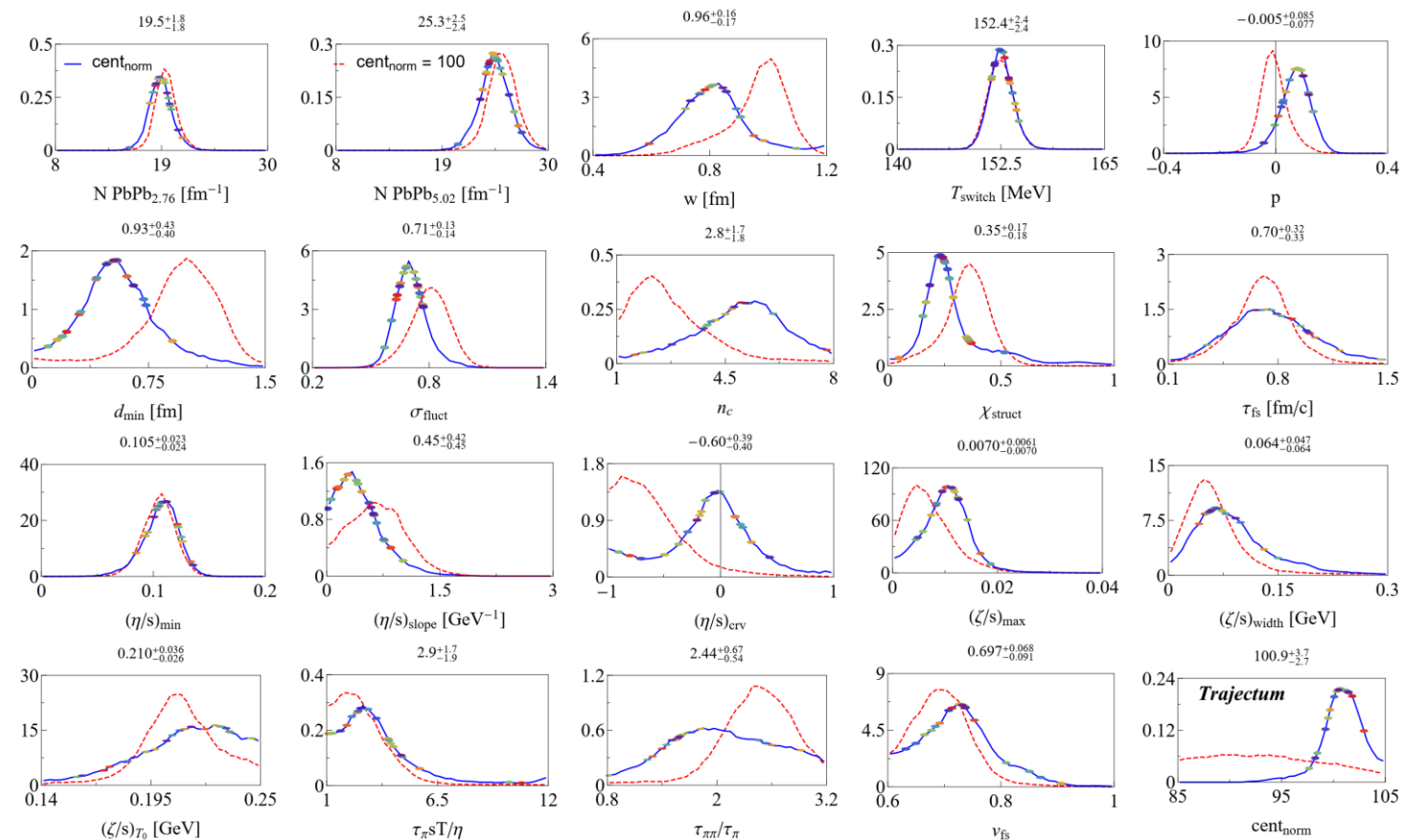
Posterior distributions

1. Dashed: standard $cent_{\text{norm}}$
 - Emulation effects for $cent_{\text{norm}}$ itself
2. Solid: posterior distributions
 - More accurate than previously

Also indicated: 20 randomly drawn points

-> allows for systematic uncertainties

3. This work: take MAP

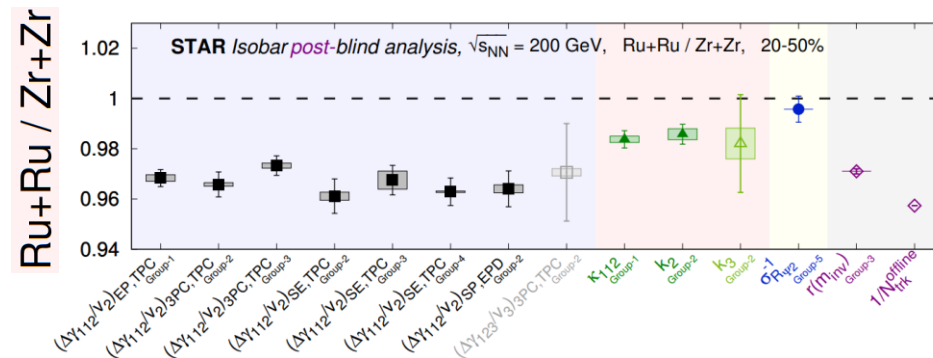


Isobar collisions at STAR

Varying the magnetic field

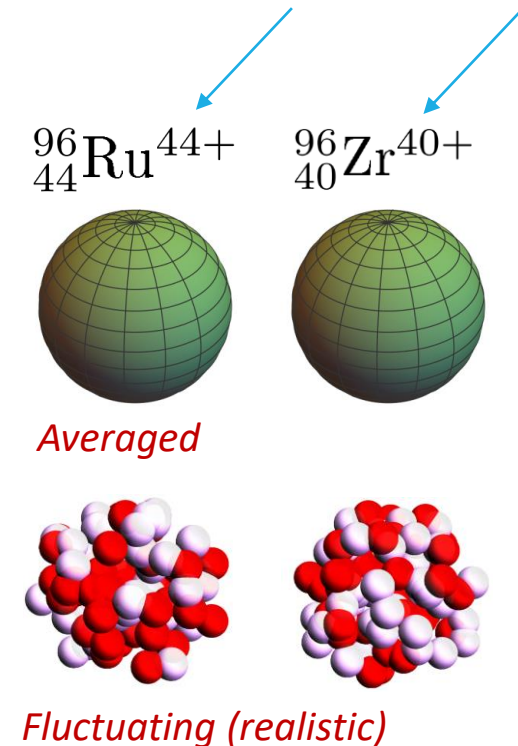
Idea: similar nuclei (same # of baryons), different charge

- Ruthenium generates a 10% larger magnetic field
- Ideal set-up to suppress background and detect Chiral Magnetic Effect (CME)
- Very precise blinded analysis by STAR:



CME-like

No CME

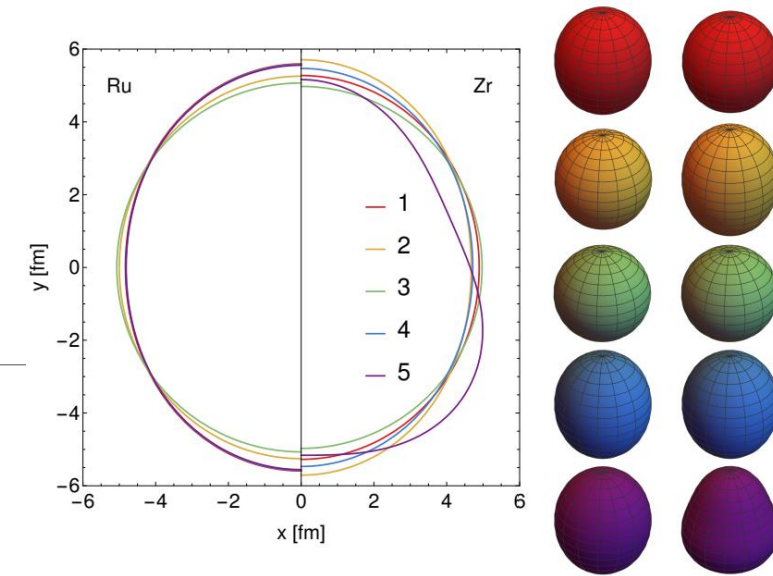


Unfortunately (?), no CME detected

Isobar collisions at STAR

Five different cases simulated:

nucleus	R_p [fm]	σ_p [fm]	R_n [fm]	σ_n [fm]	β_2	β_3	σ_{AA} [b]
$^{96}_{44}\text{Ru}(1)$	5.085	0.46	5.085	0.46	0.158	0	4.628
$^{96}_{40}\text{Zr}(1)$	5.02	0.46	5.02	0.46	0.08	0	4.540
$^{96}_{44}\text{Ru}(2)$	5.085	0.46	5.085	0.46	0.053	0	4.605
$^{96}_{40}\text{Zr}(2)$	5.02	0.46	5.02	0.46	0.217	0	4.579
$^{96}_{44}\text{Ru}(3)$	5.06	0.493	5.075	0.505	0	0	4.734
$^{96}_{40}\text{Zr}(3)$	4.915	0.521	5.015	0.574	0	0	4.860
$^{96}_{44}\text{Ru}(4)$	5.053	0.48	5.073	0.49	0.16	0	4.701
$^{96}_{40}\text{Zr}(4)$	4.912	0.508	5.007	0.564	0.16	0	4.829
$^{96}_{44}\text{Ru}(5)$	5.053	0.48	5.073	0.49	0.154	0	4.699
$^{96}_{40}\text{Zr}(5)$	4.912	0.508	5.007	0.564	0.062	0.202	4.871



1. e-A scattering experiments(STAR case 1)
2. Theory (finite-range liquid drop model, STAR 2)
3. DFT with neutron skin (spherical) [1]
4. DFT with neutron skin (deformed, $\beta_2 = 0.16$) [1]
5. As 4, but with β_2 from electric transition probability and β_3 from comparing AMPT with STAR [2]

For each case we run 0.5M collisions except for case 5 (5M), 14M in total.

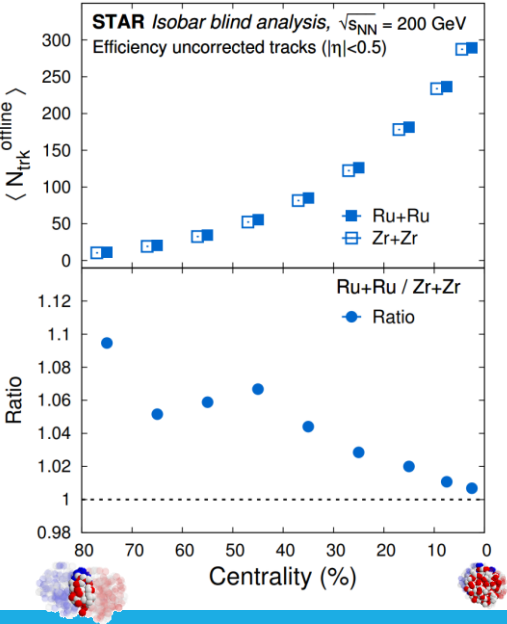
Isobar collisions at STAR - Multiplicity

Precision and non-conventional definition of centrality

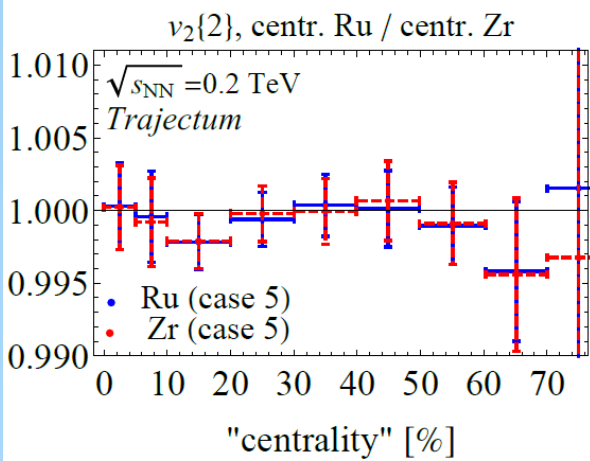
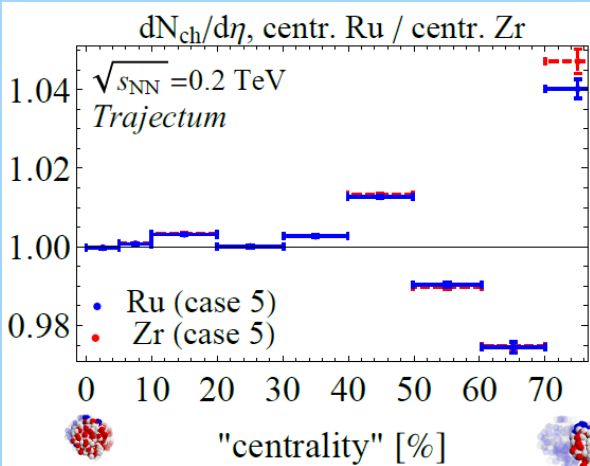
Subtlety in STAR data: “centrality label” is different for Ru and Zr

- Especially important for multiplicity (~7% effect)
- Hardly significant for other observables (<0.5% for v_2)

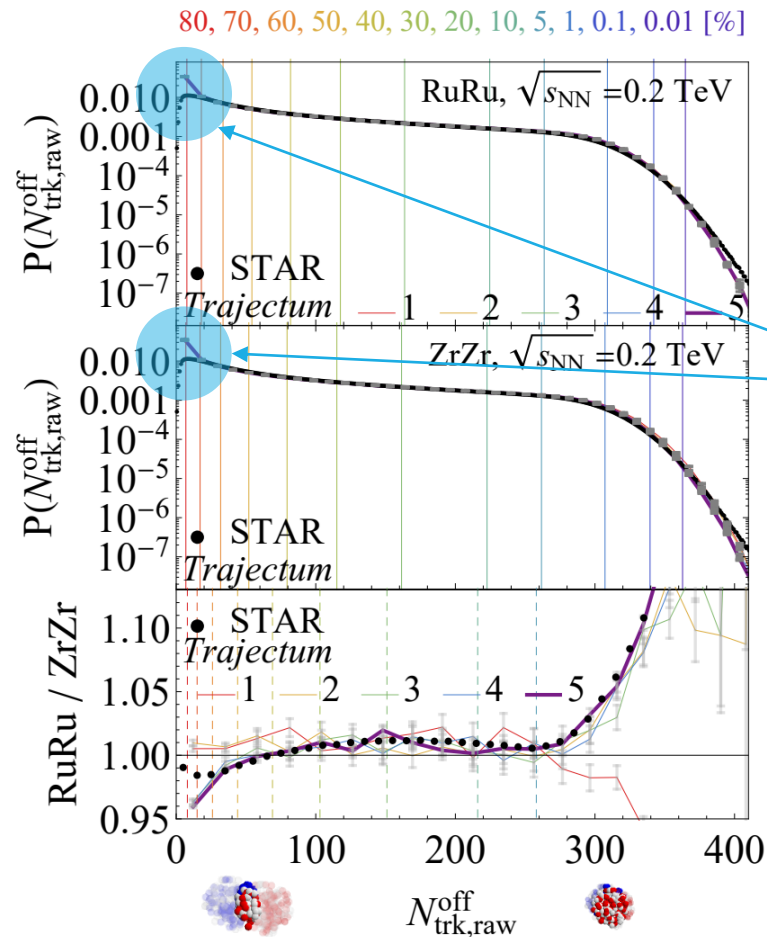
Centrality label (%)	Centrality(%)	Ru+Ru $N_{\text{trk}}^{\text{offline}}$	$\langle N_{\text{trk}}^{\text{offline}} \rangle$	Centrality(%)	Zr+Zr $N_{\text{trk}}^{\text{offline}}$	$\langle N_{\text{trk}}^{\text{offline}} \rangle$
0–5	0–5.01	258.–500.	289.32	0–5.00	256.–500.	287.36
5–10	5.01–9.94	216.–258.	236.30	5.00–9.99	213.–256.	233.79
10–20	9.94–19.96	151.–216.	181.76	9.99–20.08	147.–213.	178.19
20–30	19.96–30.08	103.–151.	125.84	20.08–29.95	100.–147.	122.35
30–40	30.08–39.89	69.–103.	85.22	29.95–40.16	65.–100.	81.62
40–50	39.89–49.86	44.–69.	55.91	40.16–50.07	41.–65.	52.41
50–60	49.86–60.29	26.–44.	34.58	50.07–59.72	25.–41.	32.66
60–70	60.29–70.04	15.–26.	20.34	59.72–70.00	14.–25.	19.34
70–80	70.04–79.93	8.–15.	11.47	70.00–80.88	7.–14.	10.48
20–50	19.96–49.86	44.–151.	89.50	20.08–50.07	41.–147.	85.68



Theory: only change centrality bounds

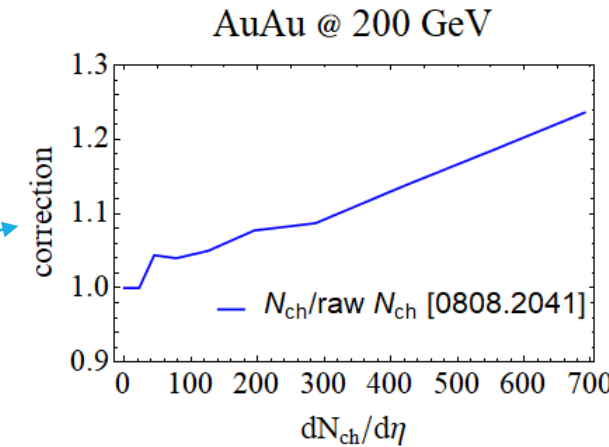


Isobar collisions at STAR - Multiplicity



Better to directly look at (raw) data

- Experimental subtlety: crucial to correct for detector efficiency
- *Trajectum* subtlety: norm not fitted to RHIC energy: multiply mult by 1.21
- Experiment misses (many) very peripheral collisions: multiply $P(N)$ by 1.31 to correct for this (not for ratio)
- Ratio experiment: normalise both and divide
Subtle: experiment unreliable for $N_{\text{trk}} < 50$
 Ratio theory: integrate **Ru+Zr experiment and Ru+Zr theory** for $N_{\text{trk}} > 50$ and require ratio to match
 Exp-theory comparison only depends on $N_{\text{trk}} > 50$

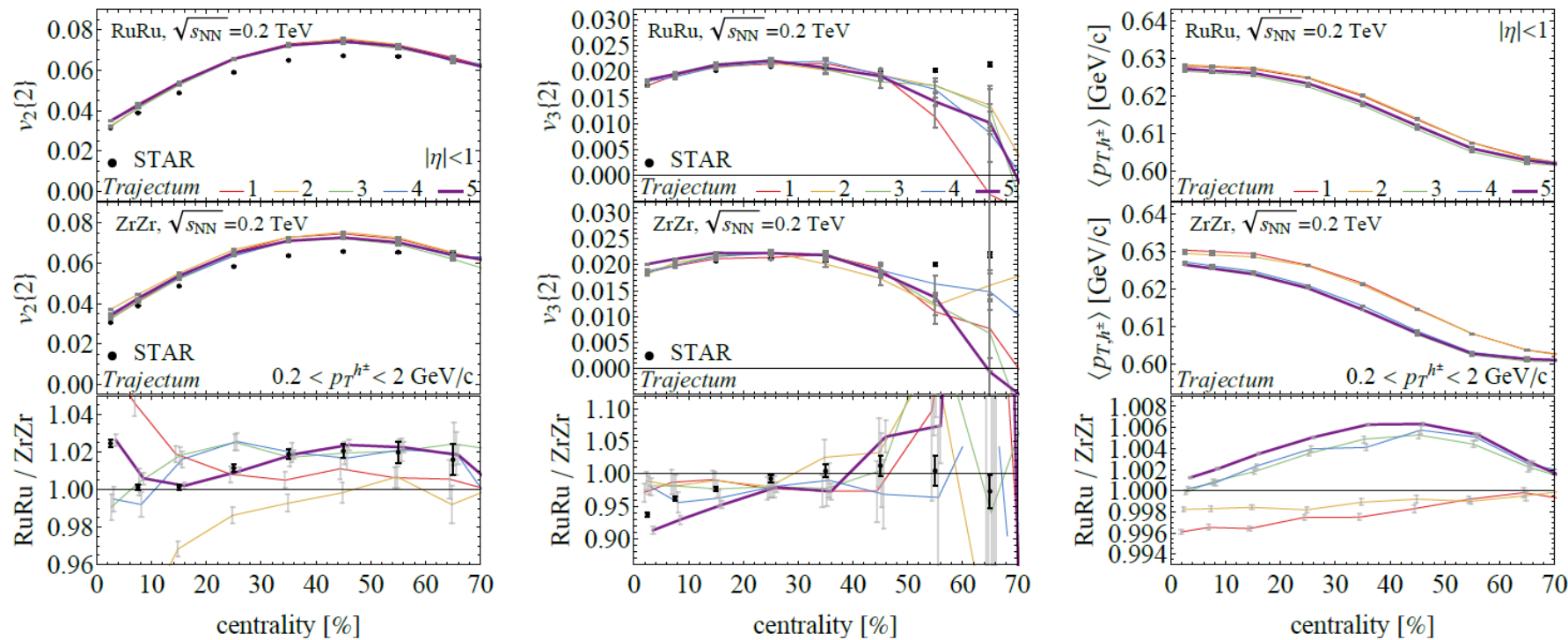


Only case 3, 4 and 5 match well over entire range (neutron-skin)

Isobar collisions at STAR – Flow and mean p_T

RuRu

ZrZr



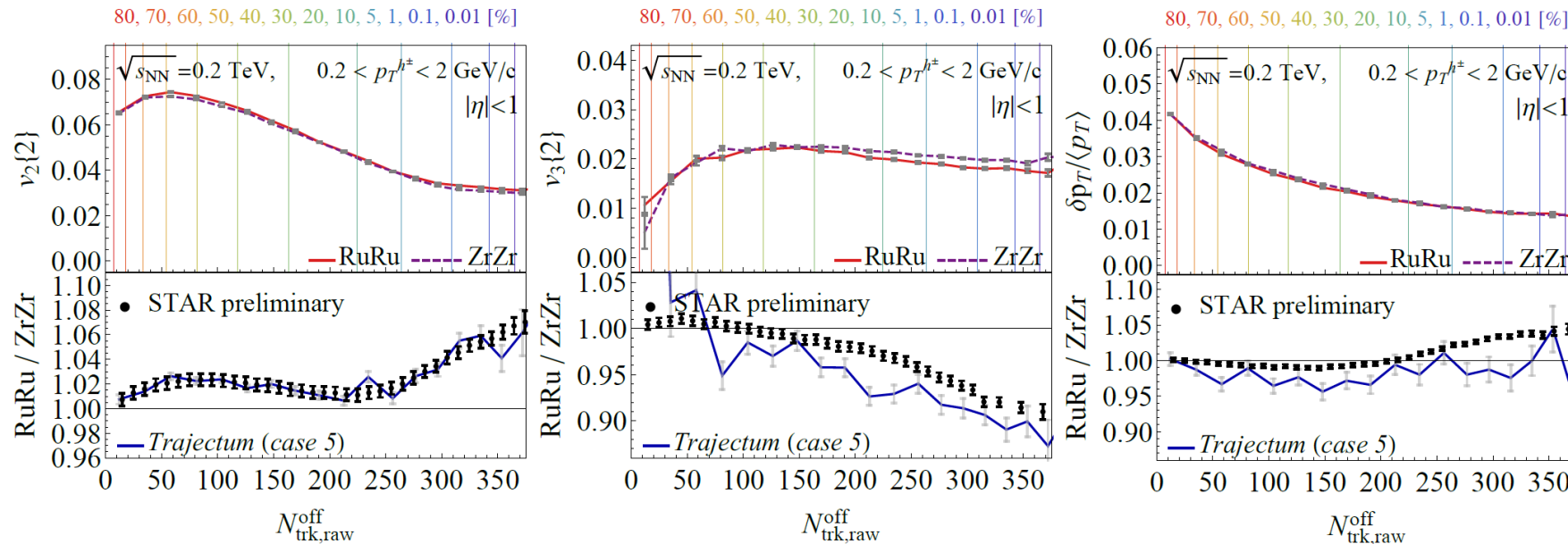
Statistics better for best case (5, with 5M collisions)

- Excellent fit, especially for v_2 ratio, v_3 ratio overestimated at central
- Note that *Trajectory* is not fitted to RHIC energies, no absolute agreement
- Mean transverse momentum is a prediction

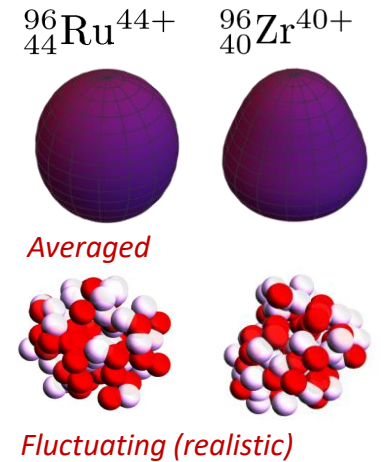
Extremely ultracentral collisions

Going to 0.01% centrality (we sample from 250M Trento events)

- Excellent match v_2 , v_3 en pt fluct somewhat overpredicted
- Extremely ultracentral is ideal regime to probe nuclear structure

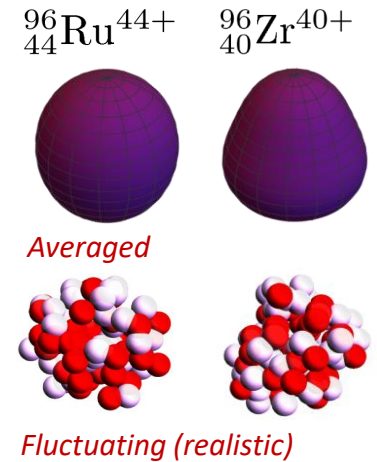
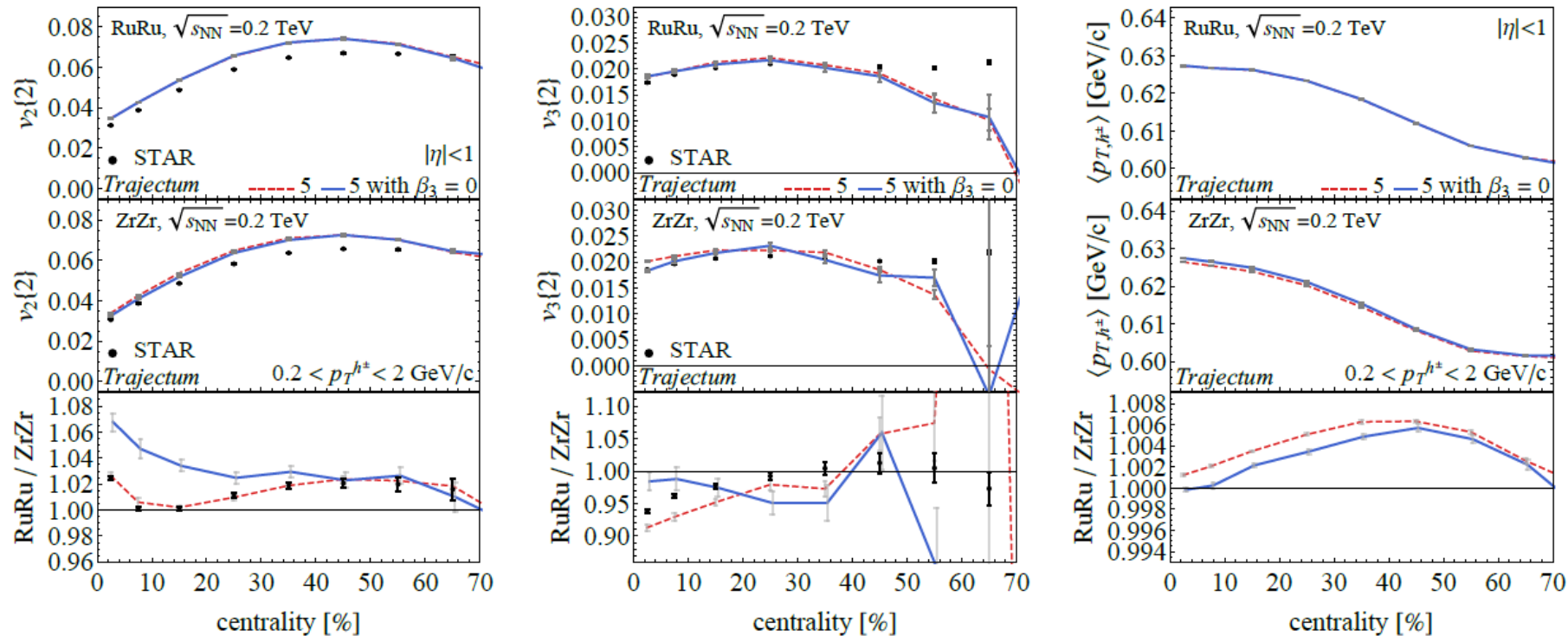


$> \beta_2$ $> \beta_3$



Effect of β_3 on observables

Clear effect on v_3 , but also on v_2 . Need a (Bayesian) refit of β_2 as well to fit v_2 and v_3 ?



Initial state predictors

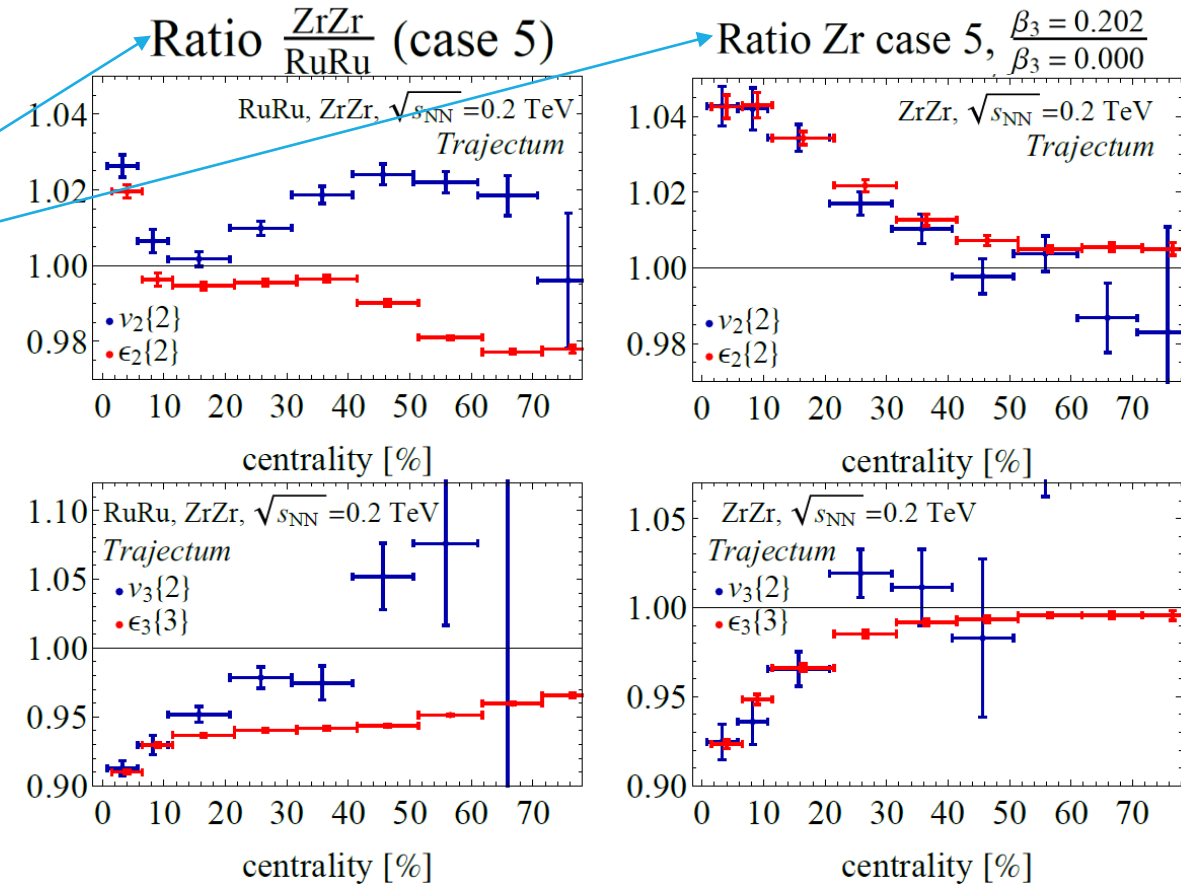
With large sample we can verify the relation

$$v_n\{2\} = \kappa \epsilon_n\{2\}$$

All else being equal this works,
e.g. within Zr as in right plots

If also size changes etc (Zr vs Ru), it can affect κ
and the initial geometry cannot be used

Unfortunate: hydro is expensive...



Discussion

Isobar collisions: an opportunity at [unprecedented precision](#)

- So many [systematics cancel](#), both experimentally and in theory
- Implies a need for statistics... of order 1M events at least to be competitive

A Bayesian point of view

- So far only performed a scan of several Wood-Saxon parameters (see also [1, 2])
- Global analysis would be preferred, but statistically hard to pull off
- Initial state predictor would be ideal, but first tests are not encouraging

Towards magnetic effects

- First things first: understanding nuclear structure. Interesting in itself (!), see also neutron stars
- Trajectum done without 3+1D or baryon number...
- Isobars still ideal setting to probe magnetic effect, but will take time to have theory at required precision

